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(Environmental health criteria ; 137)

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CONTENTS

reliable means for exposure evaluation at distances from the field source (an antenna, or a re-radiating surface) of less than about 0.2 m or $\lambda/2$, whichever is smaller. In such a case, it may be necessary to evaluate the specific absorption rates (SARs) in a model of the human body using one of the dosimetric measures (Stuchly & Stuchly, 1986), or to measure directly the RF current flowing through the person (Blackwell, 1990; Tell, 1990a).

5. DOSIMETRY

5.1 General

Time-varying electric and magnetic fields induce electric fields and corresponding electric currents in biological systems exposed to these fields. The intensities and spatial distribution of induced currents and fields are dependent on various characteristics of the exposure field, the exposure geometry, and the exposed biological system. The exposure field characteristics that play a role include the type of field (electric, magnetic, or electromagnetic radiation), frequency, polarization, direction, and strength. Important characteristics of the exposed biological body system include its size, geometry, and electrical properties. The electrical properties of biological systems described by the complex permittivity and electrical conductivity differ for various tissues.

The biological responses and effects due to exposure to electromagnetic fields generally depend on the strength of induced currents and fields. However, only the external fields can be measured easily and dosimetry has been developed to correlate the induced currents and fields with the exposure conditions. Induced currents, as a measure of dose, have been used in the quantification of experimentally induced effects in animals and the results have been extrapolated to humans.

In the broad range of frequencies considered in this publication, i.e., 300 Hz-300 GHz, two different, but interrelated, quantities are commonly used in dosimetry. At lower frequencies (below approximately 100 kHz), many biological effects can be quantified in terms of the current density in tissue. Therefore, this parameter is most often used as a dosimetric quantity. At higher frequencies, where many (but not all) interactions are due to the rate of energy deposition per unit mass, the parameter specific absorption rate (SAR) is used. The SAR is defined as "the time derivative of the incremental energy, dW, absorbed by, or dissipated in, an incremental mass, dm, contained in a volume element, dV, of a given density, ρ" (NCRP 1981). The SAR is most often expressed in units of watts per kilogram (W/kg).

by Albert et al. (1987) using chick brain tissue exposed to a few power densities of 147 MHz, amplitude modulated at 16 Hz, under anoxic and under modified media conditions designed to supply more oxygen to the tissue.

In none of these null-effect experiments did the authors reproduce the exposure conditions used by Bawin or Blackman, particularly the medium composition, power density, sinusoidal modulation, or number of samples per experiment.

Increases in calcium ion efflux have been reported in two other biological preparations. Isolated frog hearts showed enhanced calcium ion efflux at SARs of 0.00015 and 0.0003 W/kg when exposed to 240 MHz, amplitude modulated at 16 Hz (Schwartz et al., 1990). Human neuroblastoma cells exposed in culture to amplitude modulated 147 and 915 MHz at SARs of 0.005 and 0.05 W/kg displayed maximal calcium ion efflux at modulation frequencies around 16 and 60 Hz (Dutta et al., 1984, 1989). The latter experiment was conducted under natural, cell-culture growth conditions and suggests that anoxia is not an absolute requirement for sensitivity of nervous system derived cells to RF fields modulated at ELF frequencies.

Overall, the exposure-induced release of calcium ions from tissues should be viewed as contributing to the characterization of exposure conditions required to elicit a response, and, thus, to the development of an underlying mechanism of action. The efflux assay system may ultimately be useful in defining the various aspects of the physical and biological exposure conditions that sensitize and affect membrane responses to electromagnetic field exposure. It should be emphasized that insufficient information is available to define the weak field interactions. Furthermore, the reported effects cannot be characterized as a potential adverse effect on health, since little or no confirmed information has been gathered that suggests this effect occurs in animals or humans.

6.5 Indirect interactions

Electromagnetic fields, at frequencies below about 100 MHz, interact with biological bodies through electrical charges induced on ungrounded or poorly grounded metallic objects, such as cars, trucks, cranes, wires, and fences.

Two types of interaction may occur:

(*a*) a spark discharge before a person touches the object;

(*b*) the passage of current to ground through a person coming into contact with such objects; the magnitude of these currents depends on the total charge on the object. This charge, in turn, depends on the frequency and electric field strength, the object geometry and capacitance, and the person's impedance to ground.

Above a certain threshold, the current to ground is perceived by the person as a tingling or prickling sensation in the finger or hand touching the charged object, for frequencies below about 100 kHz, and as heat at higher frequencies. A severe shock can be experienced at levels much higher than this threshold. The threshold currents depend on frequency, surface of contact area, and the individual. The thresholds for effects (perception, shock, etc.) are generally higher for men than for women and children, though there are also individual differences.

All effects due to induced charges on objects are defined below in order of increasing severity:

Perception - The person is just able to detect the stimulus. There is a difference in the current perception threshold for touch and grip contact.

Annoyance - The person would consider the sensation to be a mild irritant, if it were to occur repeatedly.

Startle - If a person receives one exposure, it is sufficient to motivate the person to avoid situations that would lead to a similar experience.

The remaining reactions apply only to contact of alternating currents at frequencies below 100 kHz.

Let-go - A person cannot let go of a gripped conductor as long as the stimulus persists, because of uncontrollable muscle contraction. If a person is exposed to prolonged currents, somewhat above the let-go level, through the chest, breathing becomes difficult and, eventually, the person may become exhausted and die.

Respiratory tetanus - A person is unable to breathe as long as the stimulus is applied, owing to the contraction of the muscle responsible for breathing.

Fibrillation - Uncoordinated asynchronous heart contractions produce no blood pumping action.

Threshold currents for their occurrence are given in Table 7. Fig. 14 and 15 show threshold currents for perception and let-go, for different percentages of the population at lower frequencies. Thresholds for perception and pain (well below the let-go) were evaluated for nearly 200 men and 200 women and also estimated for 10-year-old children (Chatterjee et al., 1986). The thresholds are lower for finger contact than for grasping contact. Fig. 16 and 17 show perception and pain for finger contact (Chatterjee et al., 1986). The stimuli in both cases are tingling/pricking at frequencies below about 100 kHz and heat/warmth at higher frequencies.

Currents flowing from an object to ground through a person who touches the object can be reduced if shoes are worn (Chatterjee et al., 1986). Electric charge induced on various objects and, therefore, contact currents for people, can be calculated for a known electric field strength. Results of such calculations are shown in Fig. 18 and 19 for finger contact for males, females, and children, respectively.

RF burns can occur when current enters through a small cross-section of the body, such as a finger, when the finger contacts an electrically charged object. Another interaction that may occur at lower frequencies is a transient discharge, which occurs between a person and a charged object either by direct contact or through an air gap (Tenforde & Kaune, 1987).

Table 7. Threshold currents (mA) for various effects at frequencies ranging from 50 Hz to 3 MHz (experimental data for 50% of men, women, and children)

Effect	Subject	Threshold current (mA) at various frequencies								
		50/60 Hz	300 Hz	1000 Hz	10 kHz	30 kHz	100 kHz	300 kHz	1 MHz	3 MHz
Touch perception (finger contact)	men	0.36	(0.47)	(0.79)	4	15	40	40	40	40
	women	0.24	(0.31)	(0.53)	3.2	12	35	35	35	35
	children	*0.18*	*0.24*	*0.40*	2.5	8	25	25	25	25
Grip perception	men	1.1	1.3	2.2	15	50	300	300	300	300
	women	0.7	*0.9*	*1.5*	10	35	200	200	200	200
	children	*0.55*	*0.65*	*1.1*	9	30	150	150	150	150
Shock, not painful (grasping contact)	men	1.8	(2.3)	(3.2)	17(10)	(25)	(25)			
	women	1.2	*1.5*	*2.1*	11	*16.7*	*16.7*			
	children	*0.9*	*1.1*	*1.6*	*8.5*	*12.5*	*12.5*			
Pain (finger contact)	men	(1.8)	(2.4)	(3.3)	10	30	55	50	50	50
	women	*1.2*	*1.6*	*2.2*	6.5	23	47	45	40	40
	children	*0.9*	*1.2*	*1.6*	6	18	33	30	28	28
Shock, painful; muscle control (let-go threshold for 0.5% of population)	men	9	(11.7)	(16.2)	55	(126)	(126)			
	women	6	*7.8*	*10.8*	*37*	*84*	*84*			
	children	4.5	*5.9*	*8.1*	*27*	*63*	*63*			

Table 7 (*continued*)

Effect	Subject	Threshold current (mA) at various frequencies								
		50/60 Hz	300 Hz	1000 Hz	10 kHz	30 kHz	100 kHz	300 kHz	1 MHz	3 MHz
Burn (finger contact)	men								200	200
Painful shock, let-go threshold	men	16	18	24	75(88)	(224)	(224)			
	women	10.5	*12*	*16*	*50*	*150*	*150*			
	children	*8*	*9*	*12*	*37*	*112*	*112*			
Severe shock, breathing difficulty	men	23	(30)	(41)	94(126)	(320)	(320)			
	women	15	*20*	27	63	*214*	*214*			
	children	*12*	*15*	*20.5*	*47*	*160*	*160*			

[a] From Dalziel 1954a,b; Deno, 1974; Guy & Chou, 1982; Guy, 1985; Chatterjee et al., 1986). Data in brackets were calculated by using the frequency factors for perception thresholds and for pain and let-go thresholds, given in IEC Publication 479. Data in italics were calculated by assuming thresholds for women two-thirds of that of men and thresholds for children one-half of that for men (IEEE, 1978; Guy, 1985).

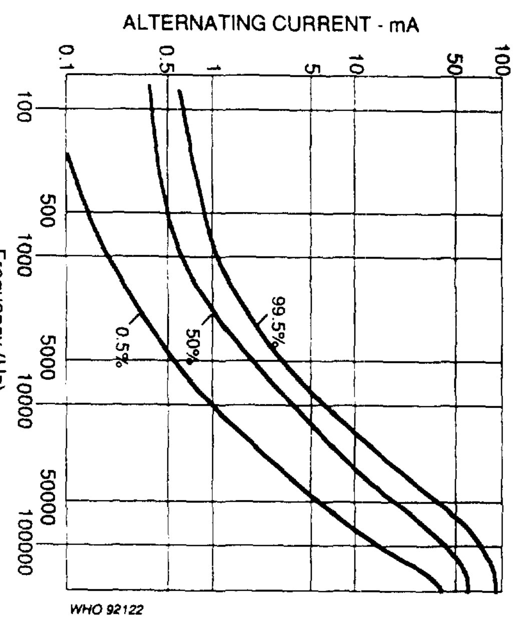

Fig. 14. Threshold currents for perception by various percentages of the population. From: EPRI (1979).

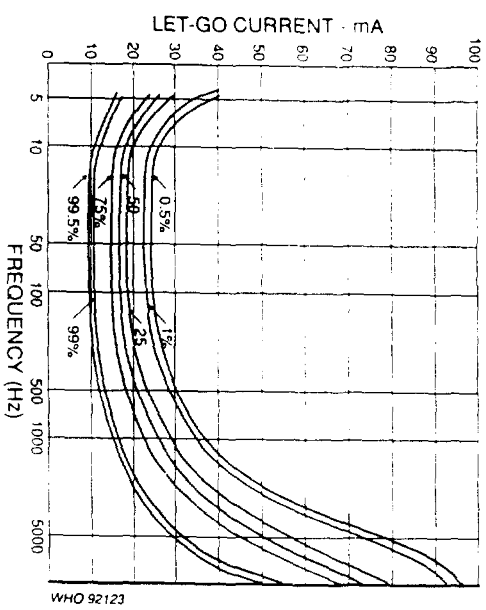

Fig. 15. Let-go currents for different percentages of the population. From: EPRI (1979).

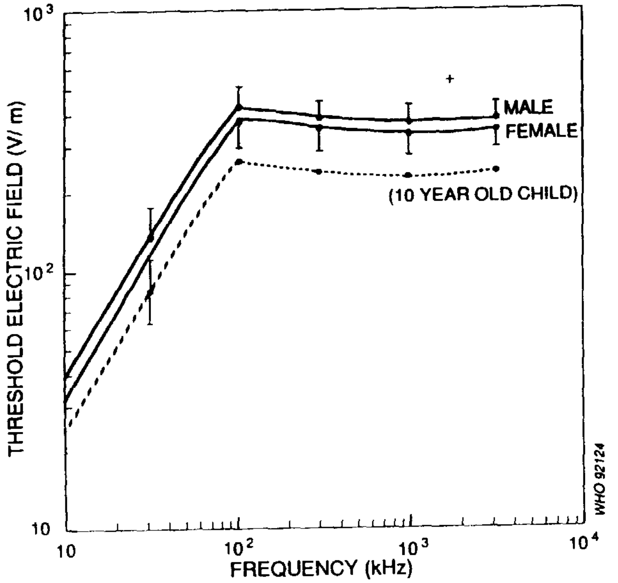

Fig. 16. Average threshold current for perception, finger contact, for adult males, females, and 10-year-old children (estimated). From: Chatterjee et al. (1986).

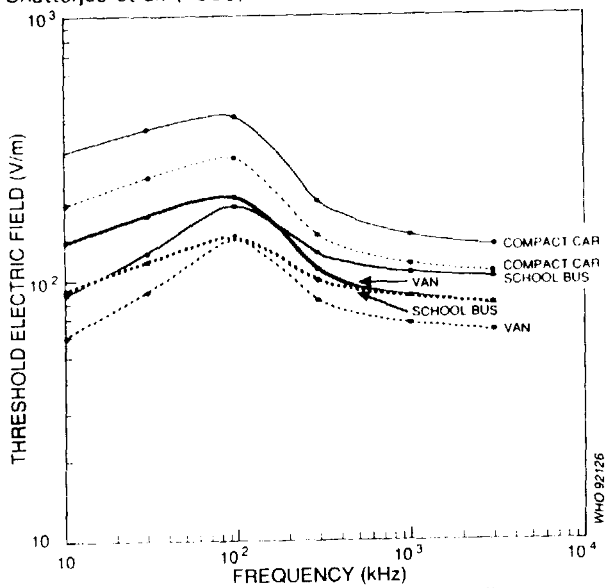

Fig. 17. Average threshold current for pain, finger contact. From: Chatterjee et al. (1986).

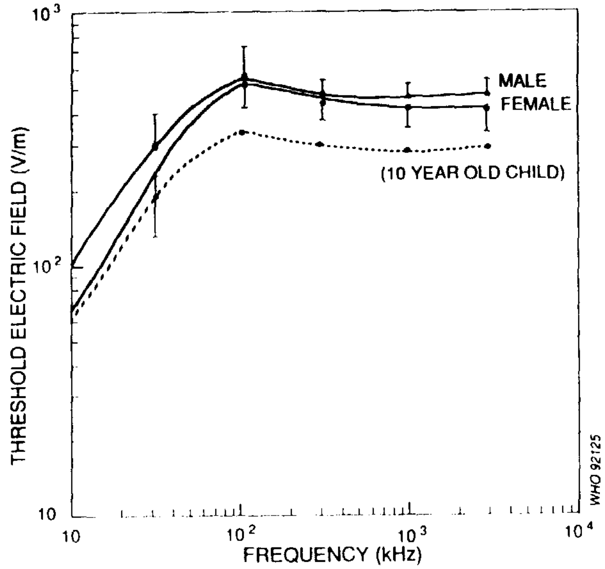

Fig. 18. Average threshold electric field for perception for grounded adult males (solid lines) and 10-year-old children (dashed line) in finger contact with various vehicles. From: Chatterjee et al. (1986).

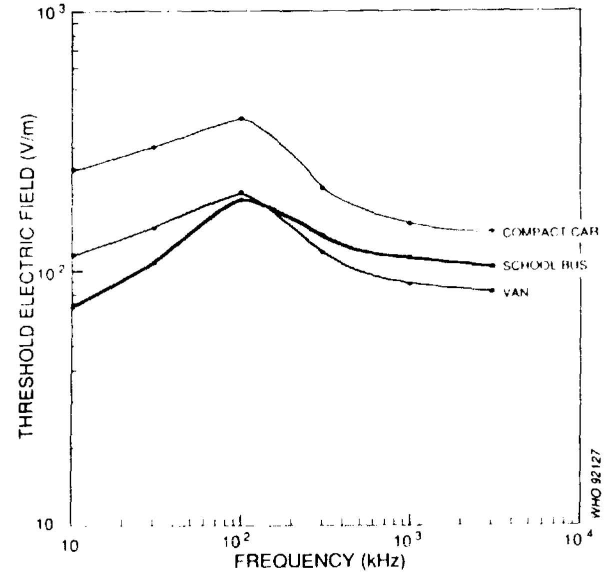

Fig. 19. Average threshold electric field for perception for grounded females in finger contact with various vehicles. From: Chatterjee et al. (1986).

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averaged over the pulse width, to 32 times the appropriate values given in Tables 34 and 35 for workers and the public; or to limit the equivalent plane-wave power density, as averaged over the pulse width, to 1000 times the corresponding values in Tables 34 and 35. In addition, the exposure as averaged over any 6 min should not exceed the values indicated in these tables.

10.4 Concluding remarks

Various approaches have produced different philosophies of protection guidelines and, thus, different exposure limits. It is apparent that, in the light of the continuous advancement of scientific results, the differences are decreasing and the revisions of existing standards or the setting of new ones reflect, at least, the tendency to merge to a common area.

The international cooperation in the development of more uniform standards should be encouraged, because the lack of international agreement on the protection standards to be used for non-ionizing radiation constitutes a major drawback for the development of safety regulations in countries where they do not yet exist (Duchêne & Komarov, 1984). Efforts, outlined above, to achieve international cooperation in the field of non-ionizing radiation together with progress in knowledge on the biological effects will, hopefully, allow protection against non-ionizing electromagnetic fields to develop in a climate of international agreement.

11. PROTECTIVE MEASURES

In situations where recommended limits can be exceeded, protective measures need to cover at least three types of potential hazards.

- exposure to RF electric and magnetic fields;
- contact with ungrounded or poorly grounded metallic objects; and
- interference with implantable and other medical devices.

A programme of measurement surveys, inspections and education on worker safety, is necessary for an effective protection programme. Protective measures can be broadly divided into three categories: engineering controls, administrative controls, and personal protection.

11.1 Engineering measures

Engineering controls for limiting human exposure to RF fields include design, siting, and installation of generating equipment. These depend on the purpose of the equipment and its operational characteristics. While strong fields around antennas of deliberate radiators, such as broadcast transmitters or radars, are unavoidable, appropriate design of the generating equipment can ensure negligibly weak fields around cabinets housing generators and other electronic circuits, and around transmission lines, such as cables and waveguides. The limitation of leakage fields at the design and manufacturing stages is more effective and less costly than later remedies, such as additional shielding, barriers, etc. At the frequency bands allocated for telecommunication, leakage (stray) fields are frequently at such low levels that they are an electromagnetic interference (EMI) problem rather than a health problem.

However, at frequencies allocated for industrial, scientific, and medical (ISM) uses, human exposure to strong stray fields is more likely to occur, as exemplified by RF industrial heaters (West et al., 1980; Stuchly et al., 1980; Eriksson & Mild, 1985; Joyner & Bangay, 1986b).

The siting and installation of deliberate transmitters must take into account exposure standards, as well as other technical considerations. It is important that an assessment of RF fields around various antennas is made and particularly, in the near-field, is verified by measurements. In siting deliberate radiators and evaluating exposure fields, the existence of multiple RF sources has to be taken into account where applicable. Often, broadcasting and other communication or navigation transmitters are located on the same tower. Furthermore, metal structures can cause reflections, and, thus, produce local enhancement of the fields. However, depending on the shape and location of the structure, it may also reduce the field. The reduction usually occurs for fields of frequencies below approximately 10 MHz. If after the erection of a radio-transmitting structure, a building is also to be erected, then it is recommended that planning authorities seek guidance as to whether the new building could reflect fields in such a way that exposure limits could be exceeded. This would entail:

(*a*) obtaining assurances from the broadcasters that the field intensities at the new site will not exceed relevant exposure limits, and

(*b*) seeking assurances from the broadcasters and the builders that the new building will not adversely affect broadcast coverage or significantly increase fields in the vicinity, due to reflections, such that the new levels exceed exposure limits.

Engineering controls against excessive contact currents include the grounding of metal fences and other permanently located metal objects, and the installation of special grounding straps on mobile metal objects. Special techniques have to be used to ensure the effective grounding of fences and other objects. Furthermore, the contact currents should be measured after the grounding of the object.

RF hot spot - a special case

Tell (1990) conducted measurements and calculations directed to applications in the VHF and UHF broadcasting bands, but the concepts are also applicable to assessing RF hot spots near AM radio stations. He summarized the problem of RF hot spots as shown below.

An RF hot spot may be defined as a point or small area in which the local values of electric and/or magnetic field strengths are significantly elevated above the typical ambient field levels and often

are confined near the surface of a conductive object. RF hot spots usually complicate the process of evaluating compliance with exposure standards, because it is often only at the small area of the hot spots that fields exceed the exposure limits.

RF hot spots may be produced by an intersection of narrow beams of RF energy (directional antennas), by the reflection of fields from conductive surfaces (standing waves), or by induced currents flowing in conductive objects exposed to ambient RF fields (re-radiation). RF hot spots are characterized by very rapid spatial variation of the fields and, typically, result in partial body exposures of individuals near the hot spots. Uniform exposure of the body is essentially impossible because of the high spatial gradient of the fields associated with RF hot spots.

Several conclusions relevant to the exposure limit compliance issue have been drawn from the results and experience of this investigation:

(*a*) In the RF hot-spot situation, involving re-radiating objects, the high, localized fields at the hot spot do not generally have the capacity to deliver whole-body SARs to exposed individuals in excess of exposure guidelines, where SARs are limited to 0.08 W/kg, regardless of the enhanced field magnitude. When the ambient RF field strengths are already at, or above, the exposure limits, the partial body exposure that accompanies proximity of the body to the object will generally increase the whole-body SAR only slightly.

(*b*) The high-intensity, electric and magnetic fields accompanying RF hot spots are not good indicators of whole-body or spatial peak SARs in the body, because of the high variability in coupling between the body of an exposed person and the hot-spot source.

(*c*) A measurement of the contact current that flows between the exposed person and a re-radiating object provides a meaningful alternative to field measurements and makes possible the evaluation of the peak SAR that may exist in a person touching the hot-spot source.

(*d*) For most practical exposure situations, when hand contact is made with a RF source, the greatest RF current will flow in the body, resulting in the worst-case situation for peak SAR. The contact case will result in significantly greater local SARs than for the non-contact condition and should be assumed to be the exposure of possible concern. This maximum SAR will be in the wrist, the anatomical structure with the smallest cross-sectional area through which the contact current can flow.

(*e*) Determining the wrist SAR for contact conditions requires a measurement of the contact current, knowledge of the conductivity of the tissues, and knowledge of the effective, conductive, cross-sectional area.

(*f*) To determine whether a particular RF source meets absorption criteria would be difficult and could be done only by a properly qualified laboratory or by an appropriate scientific body for a general class of equipment. In no case could a routine field survey determine conformance with the SAR criteria. The dosimetric procedures required for accurate SAR assessments remain complex and are relegated, for many cases, to the laboratory setting.

(*g*) Complex exposure environments, such as the interior of antenna towers, that present highly localized RF fields on climbing structures (e.g., ladders) are candidate locations where contact current measurements may prove effective in evaluating compliance with the exposure standards.

(*h*) Contact current measurements appear the only practical avenue of evaluating RF hot spots found in public environments, where ambient field levels are usually well within the standards, but local fields are apparently excessive.

(*i*) Maximum contact currents are associated with the points on a conducting object that generally exhibit the greatest surface electric field strengths. Apparently this is because such points have relatively low impedance and current is transferred when contacted by the relatively low impedance of the human body.

11.2 Administrative controls

Administrative controls that can be used to reduce or prevent exposure to RF fields are:

- access restriction, e.g., barrier fences, locked doors;
- occupancy restriction (only to authorized personnel);
- occupancy duration restriction (applicable only to workers);
- warning signs, and visible and audible alarms.

Protective measures should be applied also against ancillary hazards such as the ignition of flammable gases and detonators or blasting caps. Specific guidance on how to deal with these problems is given elsewhere (Hall & Burstow, 1980; ANSI, 1985).

11.3 Personal protection

Protective clothing, such as conductive suits, gloves, and safety shoes, can be used. However, very few are commercially available and they are useful for RF shielding only over a specific frequency range. The results of testing a few microwave suits have been published recently (Guy et al., 1987; Joyner et al., 1989). Such suits should not be used indiscriminantly. Their use should be confined to ensuring compliance with exposure standards, when engineering and administrative controls are insufficient to do so (Joyner et al., 1989). Safety shoes have been proposed to reduce high local SARs for people on the ground plane (Kanai et al., 1984). Safety glasses have also been proposed for RF protection, but there is no convincing evidence that any of them are effective. On the contrary, they may act as receiving antennas and locally enhance the field.

11.4 Medical surveillance

Medical surveillance of workers should only be instituted if, in the normal course of their work, they could be exposed to RF-field intensities that would significantly exceed the general population limits. Other than a pre-employment general medical examination to determine baseline health status, a medical surveillance programme would serve little purpose, unless workers could reasonably be exposed to RF levels that approach or exceed occupational limits.

Medical surveillance of RF workers involves:

(*a*) The assessment of the health status of the worker before commencing work (pre-employment assessment), during work, if overexposures occur, and on termination of work involving RF exposure.

(*b*) The detection and early treatment of signs of any adverse health effects that might be due to RF exposure.

(*c*) The maintenance of precise and adequate medical records for future epidemiological studies. The nature of the work and the physical parameters of RF exposure (field strengths, exposure durations, etc.) for each worker should be documented very carefully.

In many countries, the initial and periodic medical examinations of workers are a legal requirement; in others, industries and governmental agencies may require pre-employment and periodic examinations. Contraindications to employment involving RF exposure should be identified by national authorities.

Over-exposures

When RF exposure exceeding occupational limits occurs, depending on the circumstances, a medical examination may be required. It should be noted that no unique syndrome for RF exposure has been identified requiring highly specialized treatment. Treatment can be expected to be symptomatic. From very high local exposures to RF of frequencies in the GHz range, deep burns and local tissue necrosis may be observed with a long-term and severe evolution. Very strong fields in the kHz and low MHz range could result in symptoms due to involuntary muscle contractions or stimulation of nervous tissue.

When RF over-exposure exceeds occupational limits, the following is suggested (Hocking & Joyner 1988):

(*a*) The circumstances causing the over-exposure should be determined and corrected.

(*b*) An investigation should determine the extent of over-exposure of the worker(s).

(*c*) A medical examination should be conducted using data on the over-exposure to direct the type of clinical examination.

11.5 Interference with medical devices and safety equipment

The susceptibility of electronic devices, particularly emergency equipment, to interference from electromagnetic fields must be evaluated in hospitals, clinics, and industry. Certain devices are subject to interference at some frequencies at electric field strengths below those permitted in many standards (Maskell, 1985). Shielding of the devices or hospital rooms is a practical solution to the problem.

A separate concern relates to electromagnetic interference with implantable medical devices and, most prominently, cardiac pacemakers. Improvements in pacemaker design have largely eliminated their susceptibility, however, in some instances, interference may still occur (Irnich, 1984; Sager, 1987). Cardiac pacemaker wearers need to be informed by their physician about its susceptibility to electromagnetic interference. RF workers who have implanted medical devices should be evaluated prior to commencing (or resuming) work (Hocking et al., 1991).

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VOLUME 1

Biological Effects of Electric and Magnetic Fields

Sources and Mechanisms

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Phasic Behavioral and Endocrine Effects of Microwaves of Nonthermal Intensity

I. INTRODUCTION

A number of investigations have been directed at the bioeffects of nonthermal microwave exposure by looking for behavioral and endocrine changes in the organism. However, the literature on behavior after both long-term and single exposure to microwaves is contradictory. A number of studies have shown effects at single exposures to rather low-intensity (0.04–0.4 mW/cm^2) power densities (PD) (Arifulin *et al.*, 1986; Rynskov, 1985). On the other hand, other investigators have shown a lack of change in strong conditioned reflexes at power densities that induce thermal stress (de Lorge, 1983). The same experiment performed at different laboratories has not always produced the same results (Rudnev and Navakatikyan, 1981; Johnson *et al.*, 1983).

A number of investigators have reported activation effects of microwaves on the function of the higher nervous system (Akoev *et al.*, 1985; Arifulin *et al.*, 1986), especially with short-term exposure or in the first phases of long-term exposure (Akoev *et al.*, 1985; Lobanova *et al.*, 1983; Rynskov, 1985) and in following development of inhibition.

The concept that there might be phasic changes of higher nervous activity comes from the hypothesis of Simonov (1962) that the organism's reaction to a stimulus of growing intensity will, in general, have three phases: "preventive" inhibition, activation, and "overlimit" inhibition. These phases develop in the dynamic exposure and have different adaptive meanings for the organism (Garkavi *et al.*, 1979). As a rule these effects are considered to induce the state of stress, which is a real phasic process. Many studies have, therefore, been devoted to the examination of blood levels of corticosterone, ACTH, growth hormone, and thyroid hormones. The results reported are, however, contradictory and hard to interpret.

Less attention has been paid to the effects of low-intensity microwaves on the secretion of sex hormones, especially at nonthermal levels. Mikolaichyk (1987) has reported changes in concentrations of FSH and LH in hypothalamus of rats beginning with a single exposure at 0.01 mW/cm^2, while Dechaux *et al.* (1978) reported that a single exposure at an intensity of 10 mW/cm^2 caused an increased secretion of testosterone. There have been no studies of the effects of microwaves on pancreatic secretions.

Hence, the aim of our work was to study the phasic behavioral effects induced by microwave exposure and their possible connection with the endocrine system as estimated by measurement of testosterone, insulin, iodothyronine, and thyroxin in blood serum and by means of histological analysis of thyroid and adrenal glands.

II. MATERIALS AND METHODS

White Fisher-344 and inbred male and female rats aged 3–4 months were used at the beginning of exposure (120–380 g during the experiment).

Single (0.5–12 hr) and repeated (15–60 days, 7–12 hr/day) exposures were used in our experiments. The continuous wave (CW) exposure system (2450 MHz, 0.01, 0.1, 1 mW/cm^2, 0.27 mW/g) has been described earlier (Varetsky *et al.*, 1985). The irradiation was both individual (in polyethylene cages that were 17 × 24 cm and 13 cm high, closed with lattice lids on the top) and grouped (10–12 rats in each plastic cage, which was 54 × 33 cm and 20 cm high) performed in the daytime in anechoic chambers in the far field zone. The generator was a Hitachi 2M53A-58 (Japan) magnetron built in a standard rectangular waveguide on the ceiling of the chamber, which was used to generate the microwaves. Power density was controlled by a M3-51 device with a P6-32 pick-up antenna. The absorption dose of radiation, determined calorimetrically, was 0.27 mW/g for individual irradiation.

Pulsed 3000-MHz microwave irradiation (400-Hz modulation, pulse duration 2 μsec) was used (Shandala *et al.*, 1985). Radar rotation with 3, 16, and

29 rot/min frequency were imitated by packs of 20, 4, and 2 pulses every 20, 3.75, and 2.07 sec. Thus, almost equal energy was irradiated per minute—60, 64, and 58 pulses, respectively. The power densities at the cage were 0.1, 0.5, and 2.5 mW/cm^2 (±10%). The irradiation was individual (in polyethylene cages 17 × 24 cm and 29 cm high) performed either during the day or night in an anechoic chamber in the far field zone and grouped (see above).

The behavior of the animals was examined by study of the retention of active avoidance conditioned reflexes, acquired before exposure, in a shuttle-box. Since these conditioned reflexes are very stable this procedure allowed one to account for the individual peculiarities of each rat, and, therefore, the experiment had a much greater sensitivity to microwave effects (Navakatikian *et al.*, 1991). More than 30 series of experiments were performed, and repeated measurements of behavior were made on the same animals at 5, 35, and 27–33 days (only in the case of 14–15 daily exposures) after irradiation. Experiments conducted in the maze for locomotor activity measurement (Navakatikian and Platonov, 1988) did not yield sufficiently stable results (Navakatikian and Nogachevskaya, 1988).

The level of hormones in serum was assessed by radioimmunoassay using a Gamma-12 device and the following sets of chemicals: STERONE-T-125I-M, rio-INS-125I-M, rio-T3-PG, and rio-T4-PG (Institute of Bioorganic Chemistry, Byelorussia Acad. Sci., Minsk, Byeloruss). Blood samples were obtained by means of decapitating rats and then centrifuged for 10 min at 1500 rpm.

In two series of experiments, the histology of the thyroid and adrenal glands were examined after 2 months of irradiation by CW microwaves (1 mW/cm^2, 7 hr/day) and pulsed microwaves (0.1, 0.5, 2.5 mW/cm^2; 12 hr/day). The thyroid gland was examined by use of a Mallory stain and hematoxylin and eosin was used for the adrenal glands. Rats were decapitated on the second or third day after the irradiation.

III. RESULTS

A. Behavior

Changes in behavior ($P < 0.05$) are shown in Tables I and II. Since behavior was measured for 10 parameters of a single reflex, only an overall description of the behavioral change is presented. The fact that the same behavioral effects were found in a number of experiments increases the validity of the analysis.

The threshold for effects was found at rather low levels, -0.01 mW/cm^2. Weak inhibition of behavior or small changes that are not consistent in different series of experiments are characteristic to threshold levels of microwaves.

TABLE I Active Avoidance Conditioned Reflex under Pulsed Irradiation

Exposure conditions: Imitated frequency of rotation (rot/min)	Number of sessions	Duration of session (hr)	PD (mW/cm²)	Time after irradiation	Changes in behavior
16	1	0.5	0.01	0	ND
			0.01	0	Activation
			0.1	0	ND[a]
			0.1	0	Activation
			0.5	0	Activation
			2.5	0	Activation
			0.1	6-8 hr	Activation
			0.5	6-8 hr	Inhibition[b]
			2.5	6-8 hr	Activation
	1	12	0.01	0	Inhibition
			0.1	0	ND
			0.5	0	Inhibition
			2.5	0	Inhibition[c]
			0.1	6-12 hr	Activation
			0.5	6-12 hr	Activation
			2.5	6-12 hr	Activation
	14	12	0.5	3-10 hr	Inhibition[b]
				5 days	ND
16	60	12	0.1	3-34 hr	ND
			0.5	3-34 hr	ND
			2.5	3-34 hr	Activation
3	60	12	0.1	3-34 hr	Activation
			0.5	3-34 hr	Activation
			2.5	3-34 hr	Activation
29	60	12	0.1	3-34 hr	Activation
			0.5	3-34 hr	Activation
			2.5	3-34 hr	Activation

[a]Rats maintained 12 hr in individual cage before irradiation.
[b]Unexplained effects; ND, no difference.
[c]With signs of improvement of memory consolidations (achieving the criteria in five consequent conditioned responses).

With stronger single exposures, the effects are dependent on the duration of exposure. With relatively short exposure (0.5 hr), clear and consistent activation of the central nervous system was observed, while inhibition was seen with longer (6-12 hr) exposures. As a rule, action of CNS is presented upon registration of behavior in a definite interval (6-8 hr) after 0.5 hr exposure. At registration of behavior in a definite interval (6-12 hr and 4 days) after 6-12 hr exposure, the activation of CNS is restored.

TABLE II Active Avoidance Conditioned Reflex under Continuous Wave Irradiation

Exposure conditions: Number of sessions	Duration of session (hr)	PD (mW/cm²)	Time after irradiation	Changes in behavior
1	0.5	0.01	0	ND[b]
		0.01	0	ND
		0.1	0	Inhibition
		0.1	0	Activation
		1	0	Activation
	6	0.01	0	ND
		1	0	Inhibition
	7	1	1 day	ND
		1	4 days	Activation
15	7	1	17-25 hr	Activation
		1	17-25 hr	Activation
		1	17-25 hr	Activation
			35 days	Activation
		1	17-25 hr	Activation
			27-33 days	Activation
		1	17-25 hr	Activation
			27-33 days	Activation
		1	17-25 hr	Inhibition[b]
			27-33 days	Inhibition[b]
16-17[a]	7	1	After 17-25 hr + 0 hr	Activation
		1	After 17-25 hr + 0.5 hr	Activation
		1	After 17-25 hr + 6 hr	ND
60	7	1	17-25 hr	ND
		1	17-25 hr	Inhibition
		1	17-25 hr	Inhibition
		1	17-25 hr	Inhibition

[a]Registration immediately after additional single (0-, 0.5-, 6-hr) exposure after 16-17 days (1 mW/cm²) of irradiation.
[b]Unexplained effects; ND, no difference.

After repeated exposure, different phases of behavioral response were noted, characterized by activation after 15 days exposure and inhibition after 60 days. This pattern was particularly prominent with CW exposure. If after 16-17 days of exposure an additional short (0.5 hr) exposure was superimposed, this short exposure produced an extra stimulative effect, while application of an additional longer exposure (6 hr) produced an inhibitory one. After 60 days of exposure to pulsed microwaves a weak activation of the central nervous system was observed, being present in many independent series of measurements.

TABLE III Relative Changes of Testosterone and Insulin Concentrations under Pulsed Irradiation ($M \pm$ SE)

Exposure				
Number of sessions	Duration of session (hr)	PD (mW/cm^2)	*Testosterone* (%)	Insulin (%)
1	0.5	0.01	-2.5 ± 13.9	5.7 ± 13.5
		0.1	-13.4 ± 10.2	-14.5 ± 10.0
		0.5	1.3 ± 12.2	-7.9 ± 13.5
		2.5	-18.1 ± 10.9	-20.6 ± 10.6^{a}
1	12	0.01	-5.3 ± 12.6	6.2 ± 12.7
		0.1	-13.6 ± 10.6	-17.8 ± 9.8^{a}
		0.5	-24.6 ± 9.9^{b}	-23.2 ± 9.4^{b}
		0.5	-6.7 ± 13.6	-51.2 ± 13.7^{c}
		2.5	-21.6 ± 11.0^{a}	-26.5 ± 11.7^{b}
15	12	0.5	-23.3 ± 12.3^{a}	-26.3 ± 13.1^{a}
60	12	0.1	-18.3 ± 15.2	-25.8 ± 12.2^{b}
		0.5	-41.2 ± 14.9^{b}	0.6 ± 18.7
		2.5	-53.2 ± 11.8^{d}	-26.0 ± 12.2^{b}

[a] $P < 0.1$.
[b] $P < 0.05$.
[c] $P < 0.01$.
[d] $P < 0.001$ for two-way t test.

B. Thyroid Gland

A wide range of microwave exposures was studied (see Tables III and IV), but no significant differences of serum iodothyronine and thyronine concentrations were found. Histology of the thyroid gland after 2 months irradiation demonstrated increased functional activity after CW irradiation and decreased activity after pulsed irradiation at all levels (0.1, 0.5, 2.5 mW/cm^2) (for details, see Navakatikian, 1988).

C. Adrenal Glands

A study of the effects of CW irradiation (1 mW/cm^2, 7 hr/day) on adrenal structure showed an increase in functional state of the zona glomerulose, a region that plays an important role in the regulation of the mineral metabolism. This is consistent with an effect of CW irradiation on mineralocorticoid (aldosterone) secretion.

Pulsed microwaves (0.5, 2.5 mW/cm; 12 hr/day) in some of the animals caused an increase of the functional activity of zona fasciculata (which secretes glucocorticods, especially corticosterone) and in the others a decrease of the functional activity of zona reticularis (controlling secretion of androgens, mainly testosterone).

TABLE IV Relative Changes of Testosterone and Insulin Concentrations under CW Irradiation ($M \pm$ SE)

Exposure				
Number of sessions	Duration of sessions (hr)	PD (mW/cm^2)	Testosterone (%)	Insulin (%)
1	0.5	0.01	3.3 ± 14.1	-5.0 ± 13.3
		0.1	-17.1 ± 10.9	-12.0 ± 13.2
		1	-19.7 ± 9.9^{a}	-7.9 ± 12.9
	6	0.01	-2.2 ± 14.5	-9.3 ± 12.8
		0.1	-24.3 ± 11.3^{b}	-9.5 ± 12.7
		1	-33.3 ± 9.9^{c}	-5.8 ± 14.0
	7	Reg. after 1 day[d]	-6.9 ± 13.9	-3.4 ± 15.5
		Reg. after 4 day[d]	$-29.8 \pm 14.3^{+}$	-18.6 ± 15.0
15	7	1	-54.5 ± 13.6^{a}	-0.1 ± 13.7
60	7	1	-19.8 ± 17.1	24.3 ± 23.7
		1	4.8 ± 20.5	-21.5 ± 23.5
		1	2.2 ± 16.0	22.7 ± 19.8

[a] $P < 0.1$.
[b] $P < 0.05$.
[c] $P < 0.01$ for two-way t test.
[d] One session of irradiation, measurement after 1 and 4 days after exposure.

These changes of adrenal and thyroid gland histology are consistent with being a result of resistance stage of stress induced by the exposure.

D. Testosterone and Insulin

Clear and interesting changes were obtained in serum levels of testosterone and insulin following exposure (Tables III and IV). With pulsed microwaves, the level of insulin decreased at all durations of exposure (1 - 60 days). Microwave exposure also resulted in a decrease in levels of testosterone. The degree of decrease was dependent upon the power density applied. However, the effect was no longer present after 60 days of exposure to pulsed microwaves. The threshold power density was 0.1 mW/cm for both CW and pulsed microwaves.

IV. DISCUSSION

These studies have demonstrated significant effects of microwave exposure on serum levels of several hormones and that these effects are consistent and reproducible. Of particular interest is the observation that there are differences in response to pulsed and CW exposure. We interpret these hormonal changes as reflecting the organism's response to stress induced by the exposure. It is known for example that insulin levels decrease during the resistance stage of stress (Panin, 1983). Similar changes have been observed under constant magnetic field irradiation (Paltsev, 1989). A decrease of testosterone levels has even been previously linked with stress reactions, however.

The results obtained have confirmed our earlier observations on the behavioral effects at rather low levels of microwave exposure (Rudnev and Navakatikyan, 1981). The behavioral changes we observe are an initial activation that changes into inhibition as the duration of exposure is increased and is followed by a long phase of activation after the exposure is terminated. We interpret the activation effects as being a result of a stress reaction of the endocrine system and the inhibition as being a direct result of microwaves on the central nervous system.

Navakatikian and Nogachevskaya (1989) have previously demonstrated a "delayed" activation of the central nervous system using measurement of locomotor activity, seen 4 days after a single 7-hr exposure to CW microwaves, while no difference was seen 1 day after exposure. This effect has been confirmed in the present experiments, but with the use of conditioned reflexes. Thus, the delayed activation appears to be a generalized effect on the nervous system.

The observation that serum testosterone levels change following exposure (Table IV) is important and has interesting implications.

Our results suggest that microwave exposure results in phasic changes in a number of different processes and that these processes interact with each other to produce the final behavioral and hormonal alterations. The process that is seen at the lowest exposure levels may correspond to the "preventive" inhibition of Simonov (1962). We interpret this as being a direct effect on the nervous system that develops at threshold levels of exposure and, in our experiments, does not result in changes in hormonal secretion. More prolonged and intense exposure results in a stress reaction, accompanied by changes in serum levels of a variety of hormones that trigger the activation phase of behavior. There is a second process of inhibition that develops during a single exposure and is secondary to the decreased level of hormonal secretion. The third process is a slow inhibition, which develops upon repeated exposure to CW microwaves. Since at this time no effect on hormonal levels is seen, this slow inhibition appears to be a direct effect on the nervous system.

V. CONCLUSIONS

Microwaves at nonthermal levels are able to induce behavioral and endocrine changes at low power densities (0.01 - 0.1 mW/cm^2). Our studies have demonstrated several phases of inhibition and activation. We suggest that inhibition of behavior by microwaves has many mechanisms depending on the strength and duration of exposure, and most inhibitory effects result from direct actions on the nervous system. Activation, on the other hand, is correlated well with decreases in serum concentrations of testosterone and insulin. CW microwaves, however, have no influence on the secretion of insulin.

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Radio Frequency Electromagnetic Exposure: Tutorial Review on Experimental Dosimetry

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Radio frequency (RF) dosimetry is the quantification of the magnitude and distribution of absorbed electromagnetic energy within biological objects that are exposed to RF fields. At RF, the dosimetric quantity, which is called the specific absorption rate (SAR), is defined as the rate at which energy is absorbed per unit mass. The SAR is determined not only by the incident electromagnetic waves but also by the electrical and geometric characteristics of the irradiated subject and nearby objects. It is related to the internal electric field strength (E) as well as to the electric conductivity and the density of tissues; therefore, it is a suitable dosimetric parameter, even when a mechanism is determined to be "athermal." SAR distributions are usually determined from measurements in human models, in animal tissues, or from calculations. This tutorial describes experimental techniques that are used commonly to determine SAR distributions along with the SAR limitations and unresolved problems. The methods discussed to obtain point, planar, or whole-body averaged SARs include the use of small E-field probes or measurement of initial rate of temperature rise in an irradiated object.

Key words: SAR, microwave, nonionizing radiation, electric field, conductivity, biological effects

INTRODUCTION

To study the biological effects of exposure to radio frequency (RF) electromagnetic (EM) radiation, experiments that cannot be performed ethically on human beings are performed on animals, tissue preparations, and cell cultures. RF energy interactions with biological materials (in a physical sense) are complex. These interactions may produce highly nonuniform distributions of EM fields within the object, regardless of the external exposure field uniformity. The fundamental quantities associated with the interaction are the electric and magnetic field strengths induced within these tissues and the currents and energy associated with these internal fields. The internal fields and currents are related to the incident external electric and magnetic fields in a very complicated manner. The results obtained from animal and in vitro experiments are not always directly applicable to human beings. Not only are differences in biological endpoints important in RF research, one must also consider the difficult problem of extrapolating the dosimetric results from laboratory animals or cell cultures to human beings [Michaelson and Lin, 1987].

Unlike ionizing radiation (radiation at or above the ultraviolet region of the EM spectrum), lower frequency nonionizing RF radiation with the same external EM field intensity can produce significantly different levels of energy absorption. This frequency dependence, in turn.

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can cause markedly different biological effects in various animal species or tissue cultures [Johnson and Guy, 1972; Chou and Guy, 1977; Chou and Guy, 1985; Stuchly and Stuchly, 1986; Guy, 1987]. For example, after observing a behavioral effect in rats exposed to a 2450 MHz microwave field at an incident power density of 0.5 mW/cm^2, one cannot conclude that the external microwave irradiation at that frequency and power density will elicit an analogous behavioral response in human beings. By the same token, the absence of any effect on flying insects exposed to microwave radiation at 100 mW/cm^2 does not assure safety for humans exposed to that intensity. To interpret a biological effect, one must determine the internal field strength or the energy dose that can cause such an effect in the experimental subject.

In this paper, the importance of RF dosimetry, the factors affecting RF energy absorption in tissue, and the experimental methods of determining specific absorption rate (SAR) will be discussed. The quantification of SAR to be discussed includes localized, planar (two-dimensional), and whole-body measurements. RF dosimetry, per se, refers only to energy absorption in tissues and not to exposure fields external to the biological system. Instrumentation and methods for measuring external field strengths or power densities can be found in numerous publications [Stuchly and Stuchly, 1986; Michaelson and Lin, 1987; Bassen and Babij, 1990; ANSI/IEEE, 1992b]. Examples of applying these techniques to common RF sources are described in a report from the National Council on Radiation Protection and Measurements [NCRP, 1994]. The discussions herein focus primarily on the experimental aspects of SAR measurements and not on theoretical calculations for determining the SAR, such as the finite-difference time-domain (FDTD) method [Taflove, 1995]. Durney et al. [1986] and Gandhi [1990] have provided extensive information on the use of theoretical techniques. Details of SAR measurement practices can be found in the American National Standards Institute (ANSI)/Institute of Electrical and Electronics Engineers (IEEE) C95.3-1992 standard [ANSI/IEEE, 1992b]. Examples of SAR measurements relating to cellular and mobile telephones will be used to illustrate the complexity of RF dosimetry. Finally, limitations and unresolved problems associated with the use of SAR will be addressed.

BASIC RF PARAMETERS

A few fundamental parameters of external exposure to EM fields are in order. These parameters are important in establishing the SAR in a biological object that is exposed to an RF field. Some of these parameters are illustrated in Figure 1. More definitions can be found in the ANSI/IEEE documents [ANSI/IEEE, 1992a,b].

Electric field strength is a vector quantity (usually designated as E) that describes the force on an infinitesimally small electric charge at a given point in an electric field (produced by charges). The unit of electric field strength is volts per meter (V/m). *Magnetic field strength* is a vector quantity (usually designated as H) that describes the force imposed on an infinitesimally small, moving, electrically charged particle at a given point in a magnetic field (produced by current). The direction of the force is perpendicular to the direction of the field and the motion of the particle. The unit of magnetic field strength is amperes per meter (A/m).

The *EM field* is the combination of a time-varying electric field and a magnetic field at a point in space. For every time-varying electric field, there is an accompanying time-varying magnetic field, and vice versa. *Exposure* is the irradiation or immersion of a biological object in EM fields that are external to and incident upon the object. The magnitude of an exposure depends on the strength and duration of the external EM fields. *Internal fields* are the EM fields that are induced inside the tissues of a biological object by external fields.

Whole-body exposure is the exposure of a biological object when the incident electric field and/or the magnetic field strengths are relatively uniform over the entire biological object. *Partial-body exposure* is the exposure of a biological object where the incident electric field and/or the magnetic field strengths are nonuniform over the biological object. The field strengths are small over some significant portion of the external surface of the exposed object.

The *dose* or *specific absorption* (SA) is the total amount of energy that is absorbed by a given mass within a biological object exposed to external EM fields. The SA is expressed in units of joules per kg (J/kg) or W-s per kg. The *dose rate* or *SAR* is the time rate at which energy is absorbed by a biological object exposed to EM fields. The SAR is expressed in W/kg or in mW/g. For more details, see Definition of SAR, below.

The *whole-body averaged SAR* is a single SAR value that represents the magnitude of the spatially averaged SAR throughout an exposed biological object. The *local SAR* is the SAR that represents the magnitude of the SAR in a small portion of an exposed biological object.

Frequency is the number of periods of sinusoidal variation per unit time. Frequency is measured in hertz (cycles per second). In RF radiation, the unit megahertz (MHz; one million hertz) is commonly used. *Wavelength* is the distance between corresponding maxima in the electric (or magnetic) field in a medium through which an RF EM wave is propagated. Wavelength and frequency are related by the following equation:

$$\lambda = v/f,$$

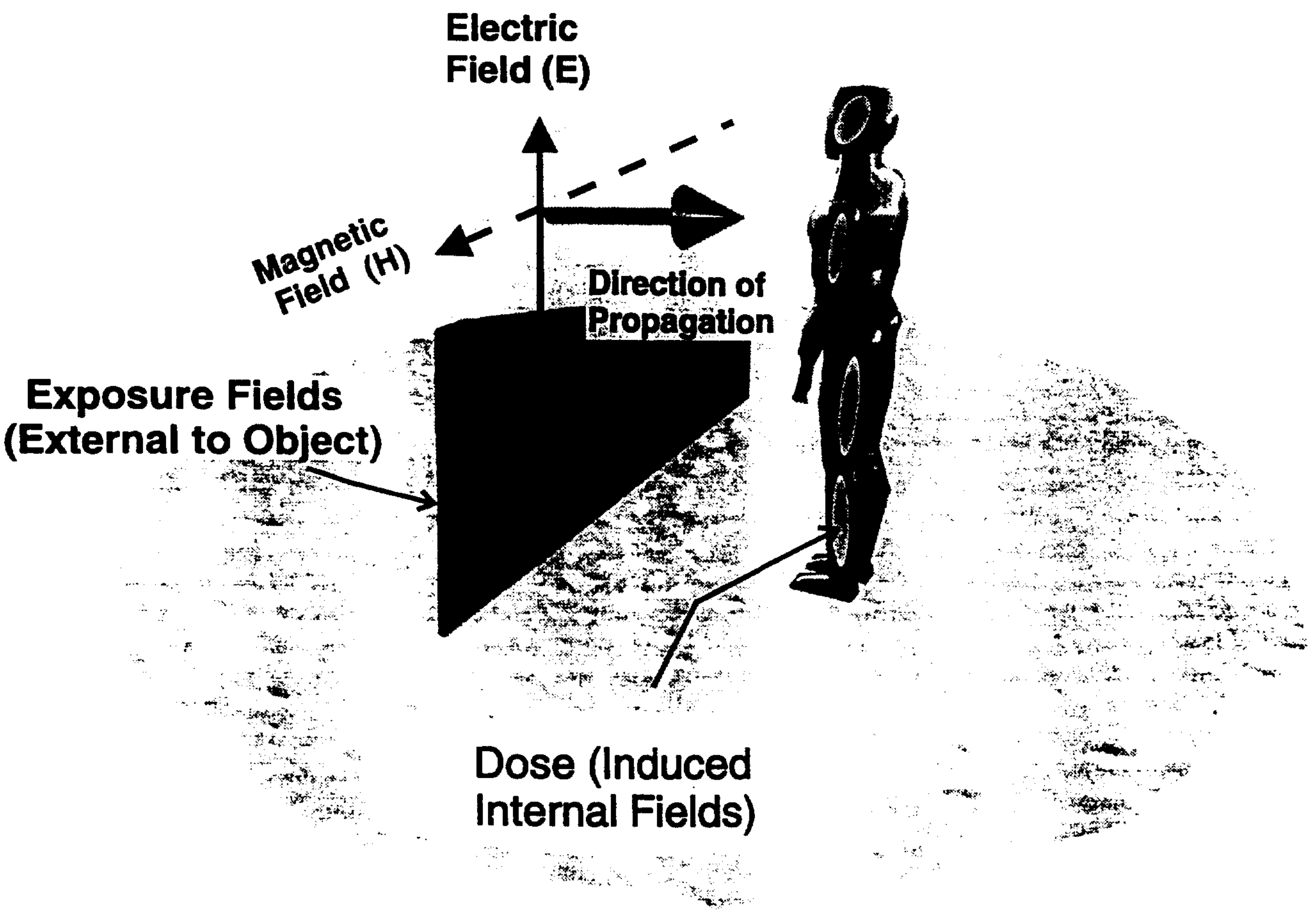

Fig. 1. Spatially uniform incident radio frequency (RF) fields and resulting nonuniform distribution of internal fields.

where λ = wavelength (meters), f = frequency (Hz), ν = velocity of EM wave in media $= c/(\varepsilon_r)^{\frac{1}{2}}$, c = velocity of light in vacuum (~3×10^8 m/second), and ε_r = relative dielectric constant of the media. For a 300 MHz RF wave propagating through air, the wavelength is about 1.0 meter.

DEFINITION OF SAR

Coupling (transferring) EM energy to tissues is a complex function of many variables. The external incident field intensity may be expressed in a variety of units. Exposure data may be expressed in terms of power density (mW/cm^2), external electric field strength (V/m), or magnetic field strength (A/m). None of these data provides investigators with sufficient insight into how fields interact with biological tissue. A basic physical law (that of Grotthuss-Draper) states that a physical agent will have an effect only if it is inside a body. Consequently, the question arises as to the most suitable parameter(s) for quantifying the interaction of EM fields and biological systems. Schwan [1971] proposed the use of induced current density in tissue. An alternative is to use the internal electric field strength (E). Yet another option is to use the mass-normalized rate of energy absorption, or dose rate, a concept that was introduced to microwave research in the late 1960s [Justesen and King, 1970; Justesen, 1975]. Many investigators now rely on dose rate, which was formerly termed "absorbed power density" [Johnson and Guy, 1972]. This parameter was officially designated SAR by the National Council on Radiation Protection and Measurements [NCRP, 1981]. *The SAR is formally defined as the time derivative of the incremental energy absorbed by (dissipated in) an incremental mass contained in a volume of a given density.* The SAR definition also applies to magnetic SA (i.e., energy absorption by biomagnetite in magnetic fields). In absence the of magnetic materials, only electric fields need to be considered.

Technically, it makes no difference which of the above parameters (E, induced current, or SAR) is chosen for quantification, because they are all related by the following equations:

$$SAR = \frac{\sigma}{\rho} E^2 \quad (W/kg), \tag{1}$$

$$E = \left(\frac{\rho}{\sigma} SAR \right)^{\frac{1}{2}} \quad (V/m), \tag{2}$$

$$J = (\sigma \rho \, SAR)^{\frac{1}{2}} \quad (A/m^2). \tag{3}$$

The heating rate (HR) used in clinical hyperthermia applications [Chou, 1990] is also related to the SAR:

$$HR = \frac{SAR}{69.77 c_H} \quad (°C/\min). \tag{4}$$

where E is the root-mean-square value of the induced electric field strength (V/m) in tissue, J is the current density (A/m^2) in tissue, ρ is the tissue density in kg/m^3, σ is the dielectric conductivity of the tissue in Siemens/m, and c_H is the specific heat capacity of the tissue in kcal/kg· °C.

ANSI was the first to adopt SAR as the fundamental dosimetry parameter for the RF exposure safety standard [ANSI, 1982]. No matter which of the parameters is used, the essential result is the quantification of the EM field in irradiated tissue. Among these parameters, SAR has been accepted widely as the quantification unit by researchers studying biological effects and medical applications of EM fields. Without quantitative measurement of the energy or field within an exposed object, it is difficult to compare research results from various animal species and different EM exposure parameters. Also, it is impossible to extrapolate biological effect research results to human beings in order to develop RF exposure safety guidelines.

In dosimetry studies, the SAR is treated as a linear quantity. The SARs obtained at high intensities and short exposures can be extrapolated to low-power exposure. Because the thresholds for biological effects may be frequency and modulation dependent, these parameters must also be specified in addition to the SAR data.

FACTORS THAT DETERMINE ENERGY ABSORPTION IN TISSUES

Dielectric Properties

The magnitude and spatial distribution of EM fields within biological tissues depend on the dielectric properties of tissue (dielectric constant and conductivity), which are dominated by the water content. Therefore, tissues can be divided into those with high water content, such as eye, muscle, skin, liver, and kidney, and those with low water content, such as fat and bone. Recently, Gabriel [1995] reported that bone material has a higher dielectric constant and conductivity than previously published. These results are being examined further. Other tissues that contain intermediate quantities of water, such as brain, lung, and bone marrow, have dielectric properties that lie between tissues with high and low water content. The dielectric constant and conductivity of tissues vary over a wide range and are frequency dependent. Data on tissue dielectric properties can be found in Johnson and Guy [1972], Durney et al. [1986], Foster and Schwan [1986], Michaelson and Lin [1987], Stuchly and Stuchly [1990], and Gabriel [1995].

Tissue Geometry and Size

The highest local SAR is usually at or near the surface of an externally exposed object. For curved surfaces and "resonant objects," high SARs ("hot spots") exist at various locations. A complex biological system, such as a human body, consists of multiple layers of tissue. Each layer has different dielectric properties and forms an EM boundary. When exposed to an RF field, the field propagates within the multilayered object. A portion of the energy is reflected from each boundary, and a portion is transmitted into the next layer. The amount of transmission and reflection at each boundary depends on the difference in dielectric properties of the tissues (characteristic impedance mismatch). Fat thickness, tissue curvature, and dimensions of the body, limbs, and head relative to the wavelength all affect the energy distribution. Johnson and Guy [1972], Durney et al. [1986], and Lin [1986] showed different absorption characteristics in spheroidal and cylindrical biological objects of various sizes exposed to incident plane waves.

Tissue Orientation and Field Polarization

It has been shown both theoretically [Durney et al., 1978] and experimentally [Gandhi et al., 1977] that the SAR in an exposed subject is maximal when the long axis of the body is parallel to the direction of a uniform external electric field. For example, consider a rat-sized ellipsoidal model exposed to a 10 MHz RF field with the electric field parallel to the long axis of the model. The average SAR is about 20 times higher than that occurring when the electric field is perpendicular to the long axis of the model. This example illustrates that, at this frequency, energy coupling in a freely moving rat exposed to a constant power density RF field may vary by about 20-fold, depending on the field or body orientation. The ratios are different at other frequencies. For in vitro experiments, Meltz et al. [1988] showed the orientation effect of a tissue culture flask on the SAR.

Field Frequency

In addition to the frequency dependence of dielectric properties, the strength and spatial distribution of internal fields also vary with frequency. For example, the local SAR was computed for a spherical head model with a constant intensity exposure at frequencies from 100 to 10,000 MHz. The computed maximum local SAR varied by more than 100 times [Johnson and Guy, 1972]. Calculation of the variation of average SAR with frequency for a human-sized sphere showed that, at low frequencies, the average SAR varies as the square of the frequency. At intermediate frequencies, the average SAR increases directly in proportion to frequency and reaches a maximum at the resonance frequency [Lin et al., 1973]. In another theoretical study, SAR calculations for exposed ellipsoids showed that absorption increases proportionally with the square of the frequency. The local SAR reaches a maximum at a specific frequency, i.e., whole-body resonance. At resonance, the length of the long axis of the exposed body is approximately four-tenths of the field wavelength in air [Durney et al., 1978].

Source Configuration

Far field is a term that describes a plane-wave exposure field. A plane wave is characterized by electric and magnetic fields that are spatially uniform and mutually perpendicular (Fig. 1). The far field typically begins at a distance of $2D^2/\lambda$ from the radiating source, where D is the longest dimension of the radiating structure, and λ is the wavelength in air. In the far field, with the exception of polarization, the SAR is independent of source configuration (there is no interaction or "coupling" between the source and the object). However, in the *near field* (closer than $2D^2/\lambda$), energy coupling depends on the source shape and size, e.g., an operator's position relative to an RF dielectric heater or heat sealer [Stuchly and Lecuyer, 1985]. Kuster and Balzano [1992] have shown that, in the immediate vicinity of resonant RF current sources (such as a hand-held cellular telephone), the SAR in an exposed homogenous model is associated primarily with the current induced by the RF magnetic field. In another example, the SAR distributions of waveguide hyperthermia applicators also show strong source configuration dependence [Chou, 1992]. A water bolus is usually placed in the near field of the applicator to cool the skin and subcutaneous fat. The presence of this bolus in the near field dramatically affects the SAR distribution and coupling.

Exposure Environment

The quantity of energy absorbed by a body in an RF field depends on environmental factors. Factors include whether the subject is exposed in free space, on a ground plane, near metal reflectors, or in an electrically conductive structure, such as a resonant cavity or waveguide [Gandhi et al., 1977]. The presence of objects in the field, such as other animals in the same cage, can also cause SAR variation in an individual animal due to scattering of energy by the other animals. Nose or mouth touching can induce hot spots at contact points due to high induced current between animals. Metal implants can cause intensification and modification of SAR patterns within tissue. Electric field intensification at the tip of a metal electrode is dependent on its length and diameter as well as the frequency of the RF field [NCRP, 1981]. For example, as a result, the presence of a thin metallic electrode in a cat brain for neurological recording increased the peak SAR 50 times [Johnson and Guy, 1972].

Time-Intensity Factors

External field intensity and exposure duration are important parameters that determine the total energy absorbed by tissues. When an RF field is amplitude or pulse modulated, SAR also varies with time. Therefore, measurement of the time-averaged SAR in itself is not adequate for exposure characterization; thus, the modulation characteristics must be specified when relating the SAR to any observed effect. Also, SARs vary with the animal's position when exposed to RF fields. Therefore, when an animal moves, the SARs change as a function of time. If an animal is restrained to keep the SAR constant, then an artifactual stress can severely contaminate the biological data. The SAR levels can be controlled within a relatively narrow range by exposing freely moving animals in cavities [Justesen and King, 1970] or in circularly polarized waveguides [Guy et al., 1979; Chou et al., 1992].

MEASUREMENT OF SAR

Localized (Single-Point) SAR

Implantable E-field probe. According to Equation 1, the SAR can be calculated from an induced E-field, tissue conductivity, and tissue density. An E-field can be measured at a point or points within a tissue-equivalent "phantom" model or a biological system by an implantable electric field probe. Tissue-equivalent materials have been developed by many researchers to simulate dielectric properties of biological tissues at frequencies of interest. Formulas and procedures for preparing tissue-equivalent fat, muscle, brain, and bone for RF application have been reported by Guy [1971], Bini et al. [1984], Chou et al. [1984b], Lagendijk and Nilsson [1985], and Hartsgrove et al. [1987]. These materials can be shaped to simulate the geometry of biological objects. The E-field